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Prototype Design and Initial Test Evaluation of a Global-Positioning-System Time-Transfer Receiver (GPS TTR)

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July 27, 1982

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20. Abstract (Continued)

Observatory (USNO) time through published values of offsets of GPS time from USNO Master Clock 1. In the first field test of the receiver, at the Kennedy Spaceflight Center, portable clock measurements were made for comparison, and all measurements were referenced to USNO. Initial results demonstrate a time-transfer accuracy better than 200 ns. The results have shown possibilities for improvement in receiver performance to obtain time transfers accurate to 50 to 100 ns worldwide. Experiments are planned for late 1982 to demonstrate the improved capability.

CONTENTS

BACKGROUND	1
INTRODUCTION	1
THE NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)	4
TIME-TRANSFER METHOD	4
GPS TIME-TRANSFER RECEIVER (TTR)	5
RF Subsystem	6
Course-Acquisition-Code Generator	6
Time-Interval Measurement	6
Input/Output Terminal	6
Microprocessor	6
TIME-TRANSFER FIELD TESTS	7
CONCLUSIONS	13
FUTURE PLANS	13
REFERENCES	14

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PROTOTYPE DESIGN AND INITIAL TEST EVALUATION OF A GLOBAL-POSITIONING-SYSTEM TIME-TRANSFER RECEIVER (GPS TTR)

BACKGROUND

The Naval Research Laboratory has been involved in time transfer by satellite since the late 1960s. Initial experiments, with the NRL Timation satellites, demonstrated time synchronizations of less than 1 μ s over trans-Atlantic baselines. Out of the Timation program grew the NRL navigation-technology satellites, which provided a means of submicrosecond time transfers on a routine basis with worldwide coverage.

The NASA Goddard Spaceflight Center sponsored NRL to coordinate a joint effort to develop hardware which used the navigation-technology satellites to provide submicrosecond timing for the Mobile Laser Ranging System (MOBLAS). Time transfer via navigation-technology satellites was used by NASA and some other international organizations until these satellites were phased out in October 1979.

The last navigation-technology satellite, NTS II, was the first satellite to be launched with the Department of Defense's new navigation signal structure of the NAVSTAR Global Positioning System (GPS). NAVSTAR GPS has been designated as DOD's primary satellite navigation system to become fully operational in the mid to late 1980s. NASA has again sponsored NRL to provide accurate timing capability for the MOBLAS system as well as the new Transportable Laser Ranging System (TLRS) to be deployed in late 1982. NRL has extended the means of time transfer used with the navigation-technology satellites to GPS. A prototype receiver has been designed and tested, with initial field-test results demonstrating a time-transfer accuracy better than 200 ns. The initial results have shown possibilities for improvement in receiver performance to obtain time transfers with an accuracy of 50 to 100 ns worldwide. Experiments are planned for mid to late 1982 to demonstrate the improved capability.

INTRODUCTION

Present time-synchronization techniques with the NASA laser network rely on LORAN C and portable clocks to provide very accurate time tagging of laser ranging data. In applications where the data from two or more stations will be merged to determine baselines for geodetic work and polar-motion determinations, it is necessary that the clocks at the several stations be synchronized to within $\pm 1 \mu$ s with respect to a master clock, such as that of the U.S. Naval Observatory (USNO). Best synchronization results using the LORAN-C system have been obtained from the West Coast chain at the Goldstone, California, laser tracking station (MOBLAS 3). Figure 1 shows the time advance of the MOBLAS 3 clock relative to the USNO Master Clock for July 1980 through June 1981. The standard deviation of the fit to these data shows a time synchronization of about a half a microsecond.

MOBLAS 5, in Yarragadee, Australia, has obtained a poorer synchronization of about 4 μ s (Fig. 2) using the LORAN-C Northwest Pacific chain. Direct reception of LORAN-C signals is not possible there, and uncertainties in the path length of bounced signals cause large errors. In this

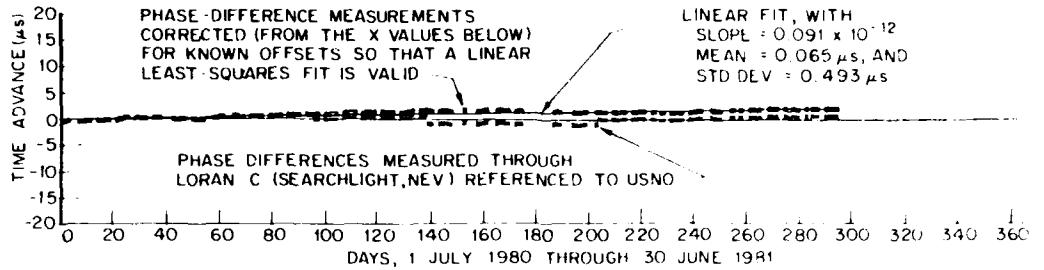


Fig. 1 — Synchronization results for the Goldstone, California, mobile laser tracking station (MOBLAS 3) relative to the USNO master clock

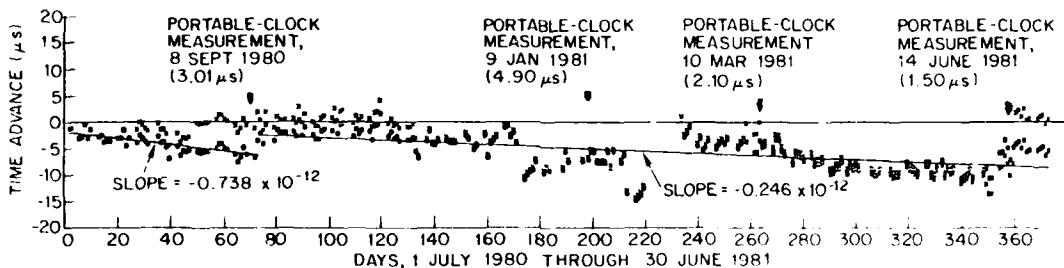


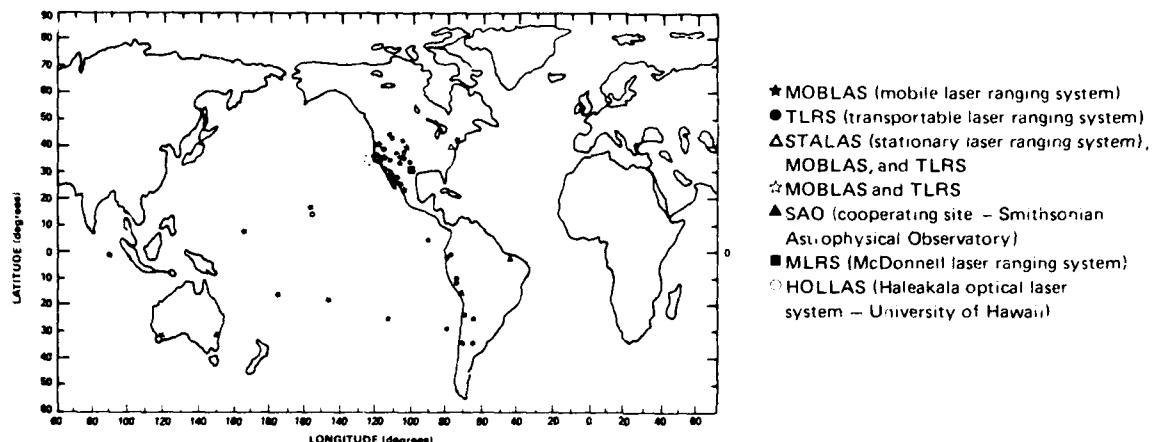
Fig. 2 — Synchronization results for the Yarragadee, Australia, mobile laser tracking station (MOBLAS 5) relative to the USNO clock as measured through LORAN C (Yap) with the aid of portable-clock measurements, since direct reception from Yap was not possible. The fit of the data to the linear segments has a standard deviation of 4.167 μ s in 240 days.

instance MOBLAS 5 required frequent portable-clock measurements (also shown in Fig. 2) to maintain microsecond synchronization.

The NASA Goddard Spaceflight Center (GSFC) and the Naval Research Laboratory (NRL) have transferred time by satellite, initially using the NRL navigation-technology satellites [1,2], with accuracies of several hundred nanoseconds being obtained [3]. As an outgrowth of that effort, a time-transfer receiver (TTR) which operates with the NAVSTAR Global-Positioning-System (GPS) satellites is presently being developed jointly by GSFC and NRL. GSFC will use the GPS TTR in the Laser Ranging Network. The network consists of eight mobile vans, a permanent installation at GSFC, and eventually four highly transportable laser systems. The laser systems will be deployed to various locations around the world (Fig. 3) and will be used in support of the NASA GSFC Crustal Dynamics Program.

NAVSTAR GPS is a tri-service Department of Defense program [4]. The first GPS satellite flown was NTS-II [5,6], which was designed and built by NRL personnel. GPS will provide the capability of very precise instantaneous navigation and transfer of time from any point on or around the earth. Six NAVSTAR satellites are now in orbit, providing instantaneous navigation over selected areas for limited parts of each day. This constellation is part of the GPS Phase I configuration, with Phase I being the system-feasibility evaluation and Phase II being the user-equipment evaluation. Additional space vehicles are to be launched as required to support the Phase I and Phase II evaluations.

NRL REPORT 8608



SITES	1980	1981	1982	1983	1984	1985	1986
FORT DAVIS TX	MOB						
MAUI HI							
EASTER ISLAND							
OWENS VALLEY CA	MOB						
DURNEY CA	MOB						
GOLDSTROM CA	MOB						
SAN DIEGO CA	MOB						
GREENBELT MD							
YARRAGABEE AUST							
AMERICAN SAMOA							
TAHITI							
HAWAII CO							
BOULDER CO							
VANCOUVER CA							
FLAGSTAFF AZ							
KWAJALEIN ATOLL	MOB						
PASADENA CA							
GREENBELT MD							
GREENBELT MD							
MAUI HI							
BAZATLAR MEX							
BATAL BRAZIL							
AREQUIPA PERU							
ORORAL AUST							
YUMA AZ							
BEAR LAKE UT							
TRINIDAD CO							
VERGEL ST							
SANTA ROSALIA MX							
SAN FELIPE MX							
TALAMA PERU							
SANTIAGO CHILE							
LA PAZ MEXICO							
ANTOFAGASTA CHILE							
LIMA PERU							
CALLOP PERU							
MANBALINA IND							
GUAYMAS MEXICO							
LOS MACHOS MEX							
BT MINE MEX							
CALAPAZOS ID							
SAN FELIX ID							
LOJA ECUADOR							
SAN JAVIER PERU							
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▲ TLRS-1 □ TLRS-2 △ TLRS-3 ▲ TLRS-4
TLRS TRANSPORTABLE LASER RANGING SYSTEM

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Fig. 3 — Sites of the NASA-GFSC laser network and the schedule for deployment of laser systems during 1980 through 1986. In the schedule, MOBLAS is abbreviated as MOB.

The major objective of the TTR is to determine precise time differences between a given satellite and a local ground clock referenced to the TTR (Fig. 4). Precise time can then be obtained between the space vehicle and a single remote ground station clock or between the space vehicle and any number of remote stations. The remote sites can then be synchronized among themselves.

THE NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)

GPS comprises three segments. The space segment consists of a constellation of satellites for global coverage [7]. The Phase III (operational) GPS will have 24 satellites, eight in each of three orbital planes. The GPS orbits are nearly circular at an altitude of approximately 10,000 nmi and inclined at 55° to the equator. The period is adjusted such that the ground trace repeats for a given ground tracking station. Each satellite transmits its own identification and orbital information continuously. The GPS has a spread-spectrum signal, formed by adding the data to a direct sequence code which is then biphase modulated onto a carrier.

The control segment consists of a master control station (MCS) and monitor stations around the world [8]. The Phase I MCS is at the Vandenberg Air Force Base, with the current supporting monitor tracking stations being at Alaska, Guam, Hawaii, and Vandenberg. The monitor stations collect data from each satellite and transmit to the MCS. The data are processed to determine the orbital characteristics of each satellite, and the trajectory information is then uploaded to each satellite once every 24 hours as the spacecraft passes over the MCS.

The user segment consists of a variety of platforms containing GPS receivers which track the satellite signals and process the data to determine position [9,10]. Coverage of the Phase III constellation is such that at least four satellites will always be in view from any point on the earth.

TIME-TRANSFER METHOD

To transfer GPS time via a GPS satellite, a pseudo-range is determined by measuring the propagation delay in the signal plus the difference between the satellite's clock and the ground station receiver's reference clock. Data from the satellite are processed to obtain satellite-position and satellite-clock information (offset from GPS time). The propagation delay is subtracted from the pseudo-range by knowing the exact locations of the satellite and the station. This difference is then

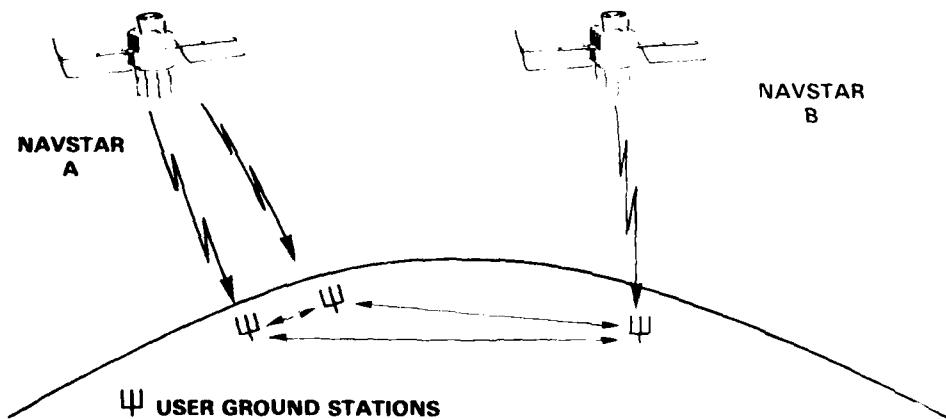


Fig. 4 — Time transfers to synchronize NAVSTAR GPS stations

corrected by the GPS time offset to determine the final result of ground-station time relative to GPS time. The Phase I GPS time is normally maintained at the Vandenberg MCS using a cesium oscillator. The Phase III GPS time is planned to be referenced from the MCS to the U.S. Naval Observatory (USNO) master clock. The final results obtained from a single-frequency receiver, such as the one described in this report, will contain a small error due to the ionospheric delay which may be modeled and corrected.

GPS TIME-TRANSFER RECEIVER (TTR)

The GPS TTR is a microcomputer-based system which is designed to replace existing receivers that formerly use the navigation-technology satellites for time transfer. The design uses hardware and software from these receivers whenever possible. The design requires that in detecting the GPS signal the TTR is to operate at the single L-band frequency of 1575 MHz, have sufficient bandwidth to track satellites throughout their doppler range from horizon to horizon, use only the course-acquisition code of 1.023 MHz, track the course-acquisition code to within 3% of a chip (30 ns), track any GPS satellite by changing to the appropriate code, and detect and decode the navigation data as required to determine a time transfer. In determining the time transfer the TTR is to rest on a stationary platform, determine the time difference between a 1-pps-input station reference and the GPS system time, measure the time difference once every 6 s, have an RMS value of less than 100 ns for the time-difference measurements, control the operation of the receiver by inputs from a keyboard, and output data to the CRT display and record data on a flexible disk. The design requires input of the antenna position in World-Geodetic-System-1972 coordinates, of the 1-pps from the station time standard, and of a 5-MHz signal from the station time standard.

With these design requirements, the receiver block diagram in Fig. 5 was implemented. The major components shown in the diagram are described in the following subsections.

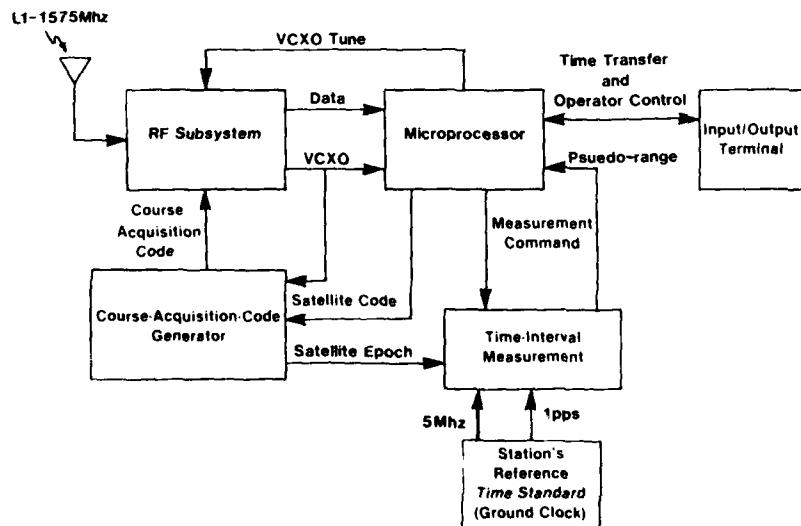


Fig. 5 — Design of the prototype GPS TTR

RF Subsystem

The RF subsystem allows tracking of both the carrier and the code forming the GPS signal. It demodulates the data message into the nonreturn-to-zero format and provides the voltage-controlled-crystal-oscillator (VCXO) frequency for coherent code generation. An external control voltage inputted to the VCXO is used for acquisition tuning.

Course-Acquisition-Code Generator

The course-acquisition-code generator accepts the code sequence of any GPS satellite from the microprocessor. It then derives the 1.023-MHz course-acquisition code from the VCXO frequency and outputs it to the RF subsystem for code tracking. A satellite time epoch is derived from the period of the course-acquisition code and outputted for the time-interval pseudo-range measurement.

Time-Interval Measurement

A time-interval counter is controlled by the microprocessor to measure the time difference between the satellite epoch and the station reference. This measurement occurs once every 6 s as commanded by the microprocessor. The time difference, which is a pseudo-range, is outputted to the microprocessor for determining the time transfer. The time-interval counter is also used to determine the VCXO frequency for tuning control.

Input/Output Terminal

The receiver contains a CRT display with a keyboard and a dual flexible-disk-drive recorder. The keyboard provides an operator interface for inputs and control of the receiver. The time-transfer results are displayed on the CRT and recorded on the flexible disks.

Microprocessor

The microprocessor controls hardware functions in the receiver, decodes the navigation message, and calculates the time transfer. The receiver is tuned during acquisition by taking frequency measurements of the VCXO, comparing these measurements to predicted values, and outputting corrections to the control voltage through a digital-to-analog converter.

The appropriate satellite course-acquisition code is loaded into the code generator after being calculated using a linear-feedback shift-register algorithm implemented in the microprocessor. The code phase is also controlled by the microprocessor until a correlation or "code lock" is established in the RF subsystem. After signal acquisition, the microprocessor decodes the navigation data and commands that pseudo-ranges be measured using the time-interval counter to calculate the final time-transfer result. This result is outputted to the CRT display and recorded on a flexible disk once every 6 s.

TIME-TRANSFER FIELD TESTS

The prototype GPS TTR was installed and tested at NASA's Merrit Island tracking site at the Kennedy Spaceflight Center, Florida. Five NAVSTAR GPS satellites, NAVSTARS 1, 3, 4, 5, and 6, were in orbit during these time-transfer tests in 1981. Figure 6a shows the horizon of the Merrit Island facility and the portion of the orbit of NAVSTAR 5 in view at the site. Figure 6b shows the orbits of all five NAVSTAR satellites along with approximate rise and set times during the GPS TTR tests. Most of the data were taken when all the satellites passed through a high elevation angle (60° to 90°) with approximately the same azimuth. Figure 6c shows the segments of each orbit along which the data collection was concentrated.

Figures 7a through 7e present data collected from individual satellite passes used in calculating the resulting difference between the Merrit Island ground clock and a given GPS spacecraft clock. On each graph a calculated time transfer is presented for an epoch close to the midtime of the observed period. The RMS value of a least-square data fit is also given. The RMS value for any one pass varies from 11 to 13 ns for a given satellite. Figure 8 is an expanded track (2 hours) of a NAVSTAR-6 pass and also shows an RMS value of 13 ns.

Figure 9 summarizes the results relating the Merrit Island clock determined through GPS, LORAN-C, and portable-clock measurements determined through GPS, LORAN-C, and portable-clock measurements. The results are presented as single points which are the average of the five satellites, with the bar at each point representing the range of the five values. The GPS results show peak-to-peak agreement with the portable clock measurements (which are considered to be truth) of 200 ns or less. During Phase I of the NAVSTAR GPS program no attempt is being made to precisely synchronize the satellites. In Phase III of the program the satellites are to be kept synchronized to within 100 ns.

NAVSTAR 1 has a quartz crystal oscillator, NAVSTARS 3 and 4 have rubidium oscillators, and NAVSTARS 5 and 6 have cesium oscillators. Figures 10a and 10b present results using the data taken from NAVSTAR 1, with a crystal oscillator, and NAVSTAR 5, with a cesium oscillator. Figure 10a shows the Merrit Island clock relative to GPS time as determined by the data from each satellite. Each point is the result of a linear least-square fit to approximately 20 min of data from an individual satellite pass. When another linear fit is performed on these day-to-day data, the results show that the time transfers have an RMS value of 25 ns and 24 ns for NAVSTAR 1 and NAVSTAR 5 respectively. Figure 10b shows the same satellite data referenced to USNO through published differences of GPS time and USNO time as determined by a GPS receiver at USNO. The time-transfer results again show RMS values of 25 ns and 24 ns. These values are within the expected noise of a single cesium oscillator to which all the data are referenced at the Merritt Island ground station.

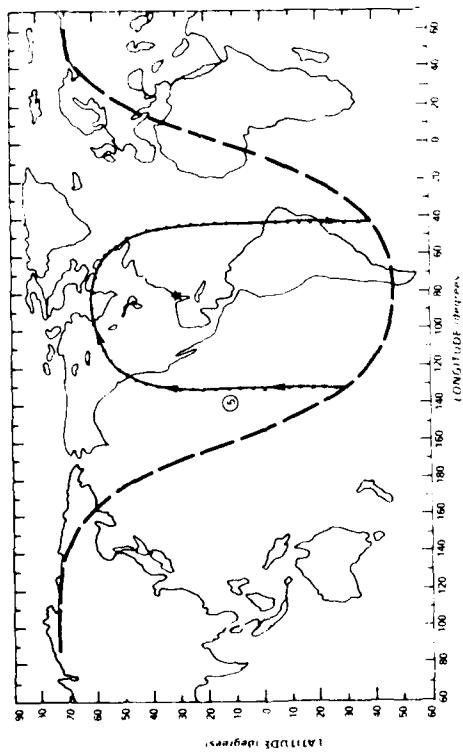


Fig. 6a — Horizon (dashed line) for the rising and setting of satellites at NASA's Merritt Island tracking site at the Kennedy Spaceflight Center. Also shown is the portion of the orbit of NAVSTAR 5 that was above the horizon in June 1981, during initial test evaluation of the prototype GPS/TTR.

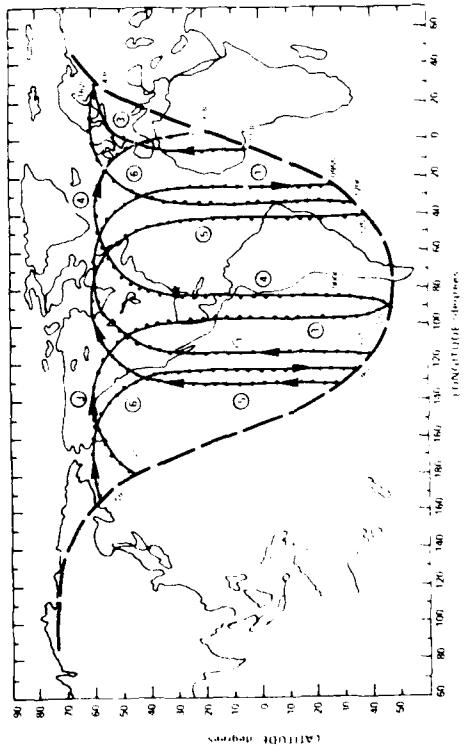


Fig. 6b — Approximate rise and set times of the orbits of all five NAVSTAR satellites in June 1981

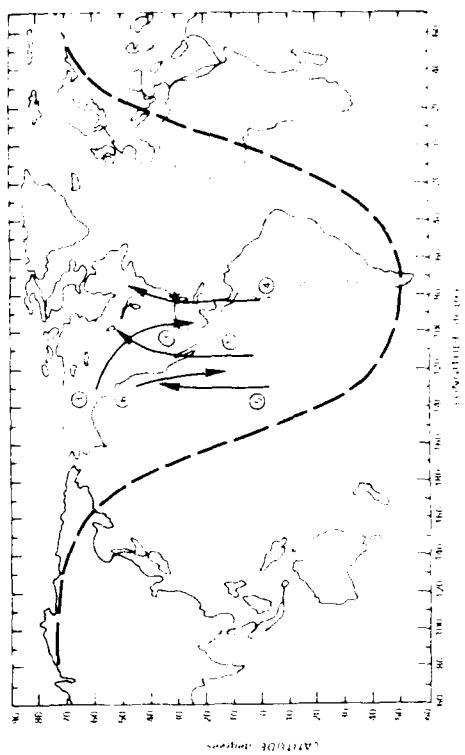


Fig. 6c — Segments of the NAVSTAR orbits along which most of the data for the initial field tests of the GPS/TTR were collected

NRL REPORT 8608

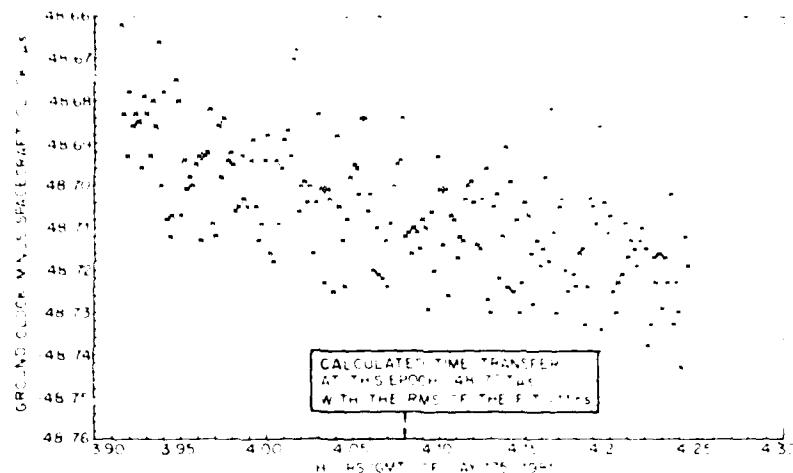


Fig. 7a — Time-transfer results from a NAVSTAR 1 pass in field tests of the GPS TTR, with the TTR's reference ground clock being compared with the NAVSTAR 1 clock. The Greenwich mean time is plotted as a decimal fraction of each hour, so that 4.08 hours, the epoch for which the time transfer was calculated, equals 4^h4^m48^s, or 0404:48.

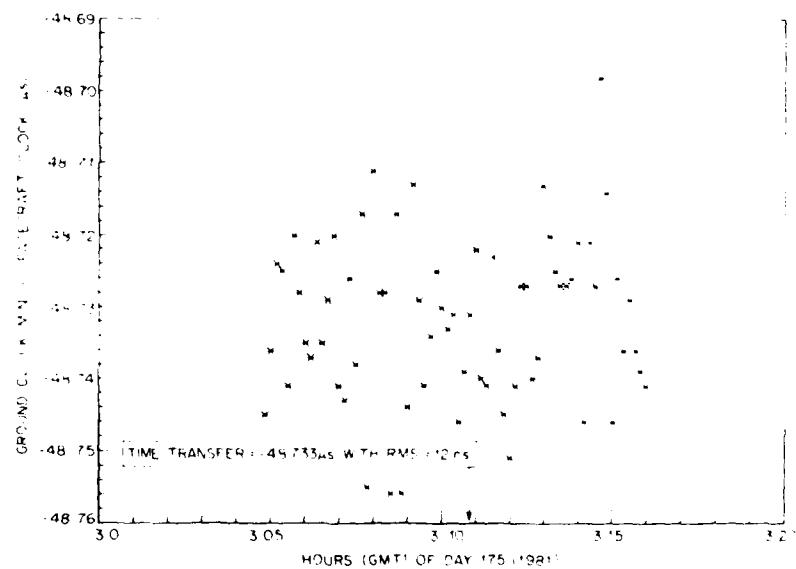


Fig. 7b -- Results from a NAVSTAR 3 pass

OAKS ET AL.

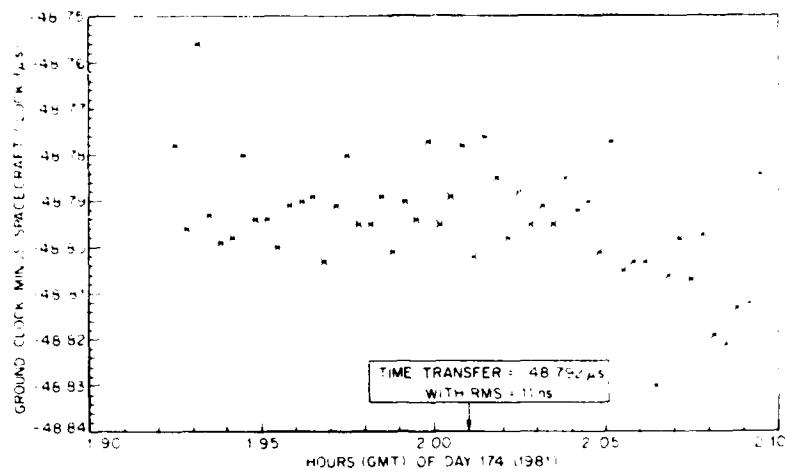


Fig. 7c — Results from a NAVSTAR 4 pass

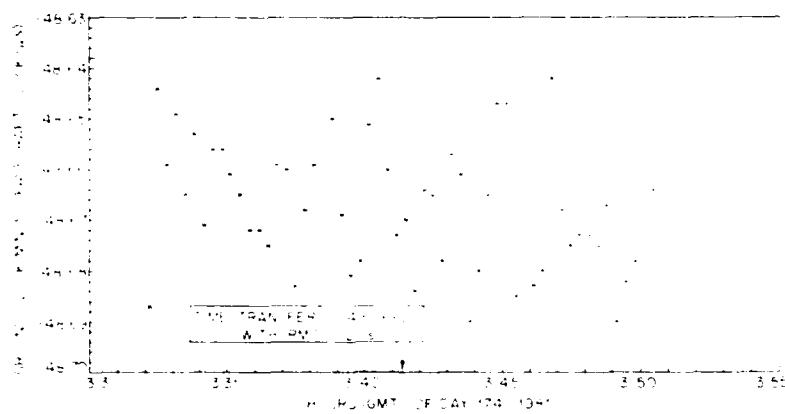


Fig. 7d — Results from a NAVSTAR 5 pass

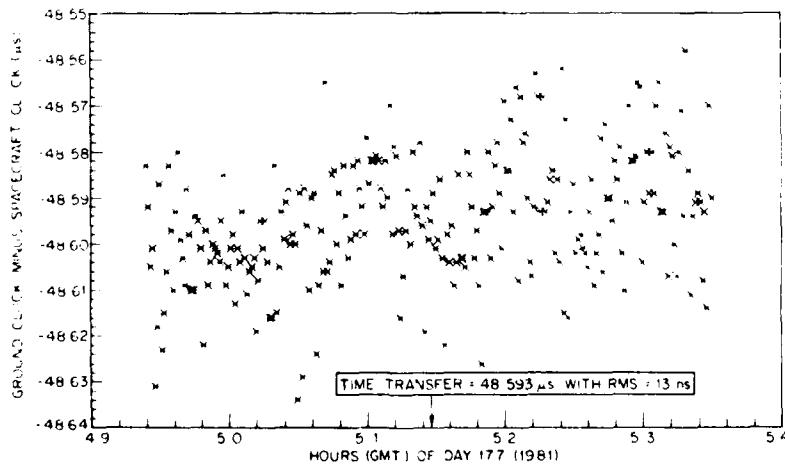


Fig. 7e — Results from a NAVSTAR 6 pass

NRL REPORT 8608

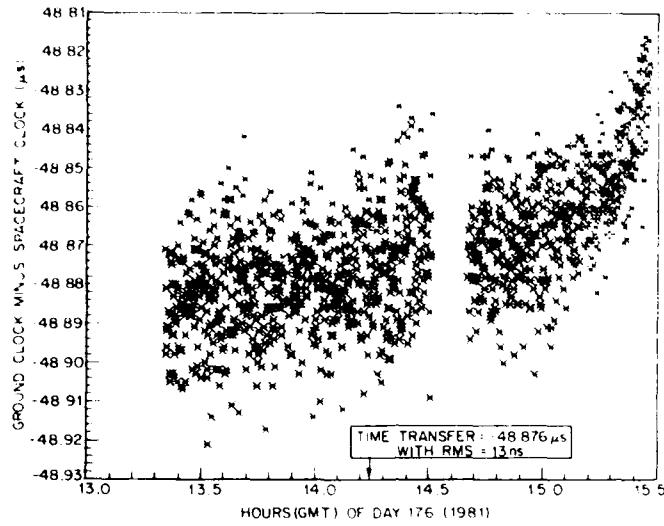


Fig. 8 — Results for an extended track of a NAVSTAR 6 pass

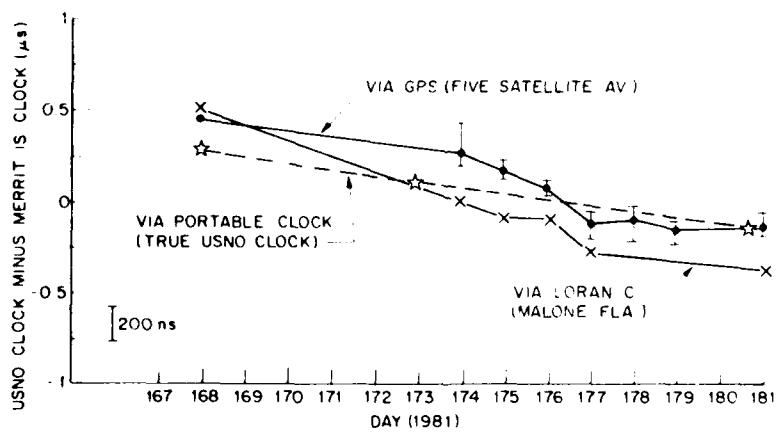


Fig. 9 — Summary of the time-transfer results from the field tests of the GPS TTR

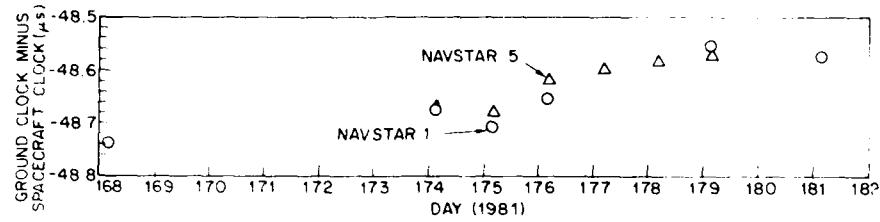


Fig. 10a — Field-test results from all the NAVSTAR 1 and NAVSTAR 5 passes

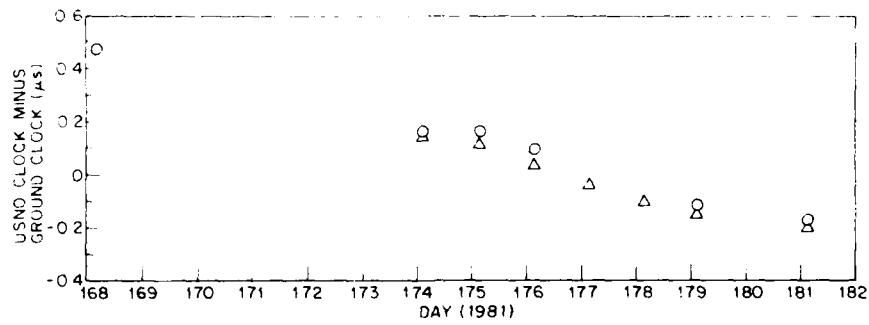


Fig. 10b — The results in Fig. 10a referenced to USNO time

CONCLUSIONS

Figure 11 presents a comparison of the resulting RMS time-transfer values for all the GPS satellites during the test. When data for a single satellite are considered, the results always yield a time transfer with an accuracy better than 100 ns. No ionospheric corrections have been made to obtain these results, and tests are planned in the future to determine how much error the ionosphere contributes. Also, it was determined that the receiver has small biases that depend on frequency. The receiver is being modified to account for these biases, and follow-on tests should demonstrate even better accuracies.

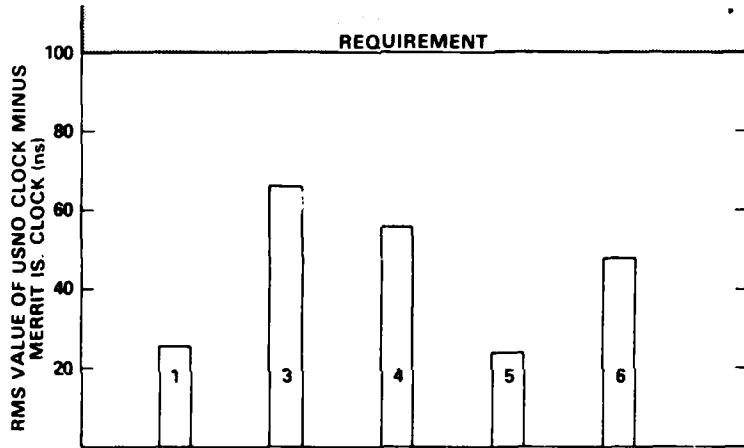


Fig. 11 — Comparison of the RMS time-transfer values for the five GPS NAVSTAR satellites

FUTURE PLANS

Development of performance and capabilities for the receiver is continuing based on results and operational feedback from field tests and ongoing experiments. Extensive evaluation of the receiver is planned through several additional field tests. A joint experiment is scheduled with the Jet Propulsion Laboratory to evaluate ionospheric delay errors. Colocation tests are planned to compare nanosecond-accuracy very-long-baseline-interferometry (VLBI) data with GPS TTR data. The colocation tests will involve VLBI stations at NRL Maryland Point, the Haystack/Westford Observatory, the NASA Deep Space Network (DSN), Goldstone, California and NASA DSN, Madrid, Spain. Future activities also include joint participation by GSFC, USNO, NBS, and NRL in the European Space Agency's SIRIO/LASSO time-transfer experiment during 1982. This experiment will use a global baseline and will provide nanosecond-accuracy laser time transfers for comparison with the GPS time transfers.

The first operational field test of the GPS TTR is scheduled for the last quarter of fiscal year 1982 with the deployment of the NASA GSFC Transportable Laser Ranging System (TLRS) prototype to Easter Island. Four additional receivers are scheduled to be deployed with mobile laser systems later in fiscal year 1982.

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